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Issues in Leading Particle and Charm Production in DIS at HERA ¹

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Abstract: A Monte Carlo simulation based on $\mathcal{O}(\alpha_s)$ QCD matrix elements matched to parton showers shows that final-state hadrons in deep inelastic scattering (DIS) can be used to tag events with a single (anti)quark recoiled against the proton. The method is particularly suited to study the mean charge of leading particles, which is sensitive to fragmentation and sea quark contribution to the proton structure function. We also discuss methods to study the charm production in DIS using the Breit frame.

1 Introduction

The quark-parton model (QPM) is a simple picture of deep inelastic scattering (DIS) which gives a basic framework for nucleon's parton distributions. Taking into account quark-gluon interactions at $\mathcal{O}(\alpha_s)$ in the leading-order (LO) approximation, this picture is modified by QCD Compton (QCDC) and Boson-Gluon Fusion (BGF) processes as shown in Fig. 1. High-order perturbative QCD emissions of partons are usually included through the parton shower mechanism in the leading-log approximation.

Nowadays, the hard QCD processes are well understood and can be modeled successfully with Monte Carlo (MC) models. This knowledge can be used to investigate various less-understood non-perturbative effects that are often obscured by perturbative QCD. For example, manifestations of instantons [1], leading particles [2] and intrinsic charm [3] in hadronic final-states of DIS are affected by the conventional perturbative QCD radiations.

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In this paper we discuss how to reduce unwanted perturbative QCD effects related to the BGF processes in the study of the nature of the struck quark at HERA energies. We suggest to constrain an event sample in order to obtain DIS events with a single struck quark recoiled against the proton (with possible initial- and final-state gluon radiations). After this selection, the resulting events have kinematic signatures similar to QPM/QCDC events. Such a selection is especially important for analysing the properties of the struck quark which carries important information on the proton structure. Using this selection, we investigate the mean charge of leading particles, i.e. hadrons emerging from the struck quark after fragmentation. Being a simple quantity to measure, the leading-particle charge is shown to be sensitive to details in fragmentation as well as the sea parton distribution inside the proton. We also investigate the production of charm in DIS by isolating the QPM/QCDC from the BGF source of charm production.

The DIS is characterised by the 4-momentum transfer $Q^2 = -q^2$ and the Bjorken scaling variable $x = Q^2/(2P \cdot q)$, where P is the 4-momentum of the proton. For the QPM in the Breit frame [4], by convention, the incident quark carries $Q/2$ momentum in the positive Z -direction and the outgoing struck quark carries the same momentum in the negative Z -direction. The phase space of the event can be divided into two regions. Particles with negative p_Z^{Breit} components of momenta form the current region. In the QPM all these particles are produced from hadronisation of the struck quark. Particles with positive p_Z^{Breit} are assigned to the target region, which is associated with the proton remnant.

The LO QCD processes, QCDC and BGF, give rise to two final-state partons leading to two jets, in addition to the proton remnant in the target region. The LO effects lead to anti-correlations between the current- and target-region multiplicities [5].

To conform the theoretical expectations discussed in this paper, we use LEPTO 6.5 [6]. This model incorporates the $\mathcal{O}(\alpha_s)$ LO matrix elements matched to parton showers (MEPS). The parton showers and hadronisation are described by the JETSET 7.4 [7]. Here it is important to emphasize a few points: We use default parameters in the LEPTO, while our results depend on the values of cut-offs on the LO matrix elements. A dependence of the results on the cut-offs values should be studied. This requires a re-tuning of the LEPTO with a new set of the cut-offs. This has not been done yet. Secondly, a MC dependence of the results should also be investigated. However, the most popular models, such as ARIADNE [8] and HERWIG [9], do not contain exact matrix elements. Thus they cannot distinguish between QPM, QCDC and BGF on an event-by-event basis, which is important for our studies. In addition, a theoretical conclusion which might be drawn from these models is far from clear due to an ambiguity in the modeling of the parton cascade.

2 BGF reduction

The two-parton production at the LO approximation can be studied in terms of five independent variables [10]. Particularly important are two of them: $x_p = Q^2/(2p \cdot q)$ and

the scaling variable $z_p = (p' \cdot p)/(p' \cdot q)$, where p is the momentum of the incoming parton and p' is that of the final-state parton. At the $\mathcal{O}(\alpha_s)$, the singularities in the two-parton cross section are given by [10]:

$$d\sigma_{2+1}^{\text{BGF}} \propto \frac{[z_p^2 + (1 - z_p)^2][x_p^2 + (1 - x_p)^2]}{z_p(1 - z_p)}, \quad d\sigma_{2+1}^{\text{QCDC}} \propto \frac{1 + x_p^2 z_p^2}{(1 - x_p)(1 - z_p)}. \quad (1)$$

In the BGF process, the poles are related to the emissions of two quarks collinear to the initial gluon or when the partons are soft ($z_p \rightarrow 1, 0$). The QCDC diverges if the radiated gluon is collinear to initial- or final-state quark or if it is soft ($z_p, x_p \rightarrow 1$). The singularity $x_p = 1$, corresponding to the gluon radiated collinear to the final-state quark, favours the production of two partons in the current regions. This effect is not present in the BGF as illustrated in Fig. 2. Indeed, according to [11], let us introduce two new variables, $z_1 = (1 - x_p - z_p)/x_p$ and $z_2 = (z_p - x_p)/x_p$, which are proportional to the longitudinal momenta of the two final-state partons in the Breit frame. For the QCDC singularities, these partons move to the current region if $z_1 < 0$ and $z_2 < 0$. For the singularities $z_p \rightarrow 0, 1$ in the BGF cross section this situation is impossible for any value of x_p . Thus, in this limit, the BGF cannot produce two partons in the current region.

To conform this expectation, we simulated the production of two final-state partons in the Breit frame using the LO matrix elements implemented in LEPTO. The parton shower and hadronisation were turned off. We used the GRV proton structure function [12] from the PDFLIB [13]. To generate DIS events, the energy of the positron and that of the proton are chosen to be 27.5 GeV and 820 GeV, respectively. The production rate for each parton configuration in the current region is shown in Fig. 3, where the notation “jet” refers to one of the LO hard partons. The BGF has many events without partons in the current region (“0 jet”). This configuration and that with a single parton in the current region (“1 jet”) are characteristic for both BGF and QCDC. At a sufficiently high Q^2 , QCDC gives rise to a fraction of events with two partons (quark and gluon) in the current region (“2 jet”).

According to this observation, the BGF contribution to DIS can be reduced following the strategy:

- To identify phase-space regions with minimum QCD radiations. DIS events at not very high Q^2 and a sufficiently large x are the most obvious choice.
- To require to detect more than one jet in the current region. This selection is likely to be possible at a sufficiently large Q^2 . At low Q^2 , the jet structure is less prominent. In this case, however, many BGF events have both jets in the target region (see Fig. 3). Therefore, for small Q^2 , one could simply require to detect at least one or two final-state hadrons in the current region.
- To restrict the transverse momentum imbalance in the current region, $P_{\text{imb}} = \sum_i p_{T,i}$, where $p_{T,i}$ is the transverse momentum of the i th particle in the current region of the Breit frame and the sum runs over all current-region particles. The QPM

leads to a single jet, collinear to the Z -direction, while the QCDC can produce two jets in the current region with well balanced transverse momenta. Therefore, $P_{\text{imb}} \simeq 0$ for these cases. In reality, of course, the imbalance is not zero due to high-order QCD effects, hadronisation or resonance decays. Fig. 4 shows the current-region transverse imbalance for charged final-state hadrons in QPM, QCDC and BGF processes simulated with LEPTO MEPS. The BGF events have the broadest distribution of P_{imb} . Thus, imposing a restriction on the P_{imb} can help to reduce the BGF events in the selected subsample.

Fig. 5 illustrates the method. Using LEPTO MEPS, we simulated DIS events before and after the cuts. We require to have at least two final-state charged hadrons in the current region and $P_{\text{imb}} < 0.7$, in order to keep the transverse current-region imbalance as small as possible but without a large reduction of the number of events passed this cut. For the default LEPTO parameters, the production rate of BGF varies from 7% to 16%, depending on x . The selection results to a subsample with only 2–4% of the BGF events. The efficiency of such selection is about 20%.

A suppression effect exists also for the QCDC, but it is not as strong as for the BGF. For the kinematic regions shown in Fig. 5, the QCDC production rate varies from 4% to 5%. After the cuts, about half of these events survive (not shown).

Note that this method is quite different to that in which one requires to observe a single jet, in addition to the remnant jet, using cluster algorithms. Our method is intended to reduce the BGF, rather than QCDC. In contrast, the requirement to observe a single jet in an event rejects both BGF and QCDC. In addition, our method is well suited to study DIS events at rather low Q^2 , independent of a jet transverse energy E_T used in jet reconstruction.

3 Mean Charge of Leading Hadrons

Below we estimate the average electric charge of a leading current-region particle, i.e. a hadron with a minimum value of p_Z^{Breit} . We expect that it is this hadron that retains main properties of the struck quark. To demonstrate a sensitivity of the leading-particle charge to details in fragmentation and sea quark production, we shall obtain this quantity analytically and using a MC simulation after the BGF reduction.

3.1 Fragmentation in the QPM

First let us find the mean charge of the struck quark in the QPM assuming that the proton consists of three valence quarks, $p = (\text{uud})$. We define the electric charge q_i of quarks u and d as $q_u = 2/3$ and $q_d = -1/3$, respectively. The virtual boson couples to the valence quark with a probability proportional to q_i^2 . Using this fact and that there are two valence quarks u and only one quark d, the probabilities P_q for the virtual boson to interact with

the valence quark $q = u, d$ are $P_u = 8/9$ and $P_d = 1/9$, respectively. The mean charge of the current region is

$$\langle q \rangle = \sum_{u,d} P_i q_i = 5/9 \simeq 0.55. \quad (2)$$

After the hard interaction, the struck quark u couples to an antiquark $\bar{q}_i = \bar{d}, \bar{u}, \bar{s}$ (the contribution from heavy quarks is neglected). Taking into account the suppression factor 0.3 for strange quarks, similar to [7], the probabilities $W^u(\bar{q}_i)$ for the valence quark u to join the antiquark \bar{q}_i are

$$W^u(\bar{u}) = 10/23, \quad W^u(\bar{d}) = 10/23, \quad W^u(\bar{s}) = 3/23. \quad (3)$$

The probabilities $W^d(\bar{q}_i)$ that this happens with the valence quark d are equal to $W^u(\bar{q}_i)$. Assuming that the fragmentation does not depend on the probability P_q for the hard interaction, the probability to find a final-state hadron h_i after the fragmentation is

$$P(h_i) = P_q W^q(\bar{q}_i), \quad q = u \text{ or } d, \quad \bar{q}_i = \bar{d}, \bar{u}, \bar{s}, \quad (4)$$

where the flavour of antiquark \bar{q}_i is taken in such a way in order to provide a correct flavour content of a meson $h_i = (\pi^0, \pi^+, \pi^-, K^0, K^+)$. The average charge $\langle q^h \rangle$ of the leading current-region hadrons is

$$\langle q^h \rangle = \left[1 - P(\pi^0) - P(K^0) \right] \sum_i q_i^h P(h_i) \simeq 0.25, \quad (5)$$

where the first factor represents the probability of observing a charged leading particle and q_i^h is the electric charge of the i th charged leading meson.

It should be noted that result (5) stays without changes even if one considers high-mass meson states: One could split $P(h_i)$ into probabilities for different multiplets, but this splitting does not affect the electric charge of a specific flavour combination and $\langle q^h \rangle \simeq 0.25$ still be valid. We have also verified that if one uses the suppression factor 0.1 for diquark production similar to [7], the contribution of the lowest-mass leading baryons (p and n) increases $\langle q^h \rangle$ by 4% only.

3.2 Contribution of sea quarks and LO QCD effects

The interactions with sea quarks change (5). If one considers the QPM type of the hard interactions with sea quarks only, the average charge seen in the current region is zero, since quarks and antiquarks can be knocked out of the proton with equal probabilities. Let us define R_{sea} as the probability of the interaction with sea quarks. Such interactions decrease the average charge by a factor $(1 - R_{\text{sea}})$, which is just the probability that the struck parton happens to be one of the valence quarks.

The first-order QCD processes further decrease (5). For the BGF events with two hard partons moving the target region and for events with a single quark in the current region, one obtains $\langle q^h \rangle = 0$ (quark and antiquark can be emitted to the current region with equal

probabilities). Therefore, this further decreases $\langle q^h \rangle$ by a factor $(1 - R_{\text{BGF}})$, where R_{BGF} is the probability for the BGF event to occur.

It is more complicated to include the QCDC process. Let us define the production rate of the QCDC events as R_{QCDC} . If only a single quark moves to the current region, this gives a similar contribution to the leading particle charge as in the QPM. However, one can notice that there is a fraction of QCDC events which does not contribute to the average charge. These events can be classified as: 1) Events with a single hard gluon moving to the current region; 2) Events without partons in the current region; 3) Events with both quark and gluon moving to the current region, in which the transverse motion of the string connecting both current-region partons cannot produce a preferable longitudinal momentum of hadrons steaming from the hadronisation of the hard parton. We define a fraction of the events for these three types as \tilde{R}_{QCDC} ($\tilde{R}_{\text{QCDC}} < R_{\text{QCDC}}$).

Taking into account all of the contributions discussed above, one obtains

$$\langle q^h \rangle = 0.25 (1 - R_{\text{sea}})(1 - R_{\text{BGF}})(1 - \tilde{R}_{\text{QCDC}}). \quad (6)$$

At a fixed Q^2 , the values of R_{sea} and R_{BGF} decrease with increase of x . Thus $\langle q^h \rangle$ rises as x increases.

From the point of view of non-perturbative physics, it is interesting to investigate the factor $0.25 (1 - R_{\text{sea}})$ in (6) which comes from our consideration along the line of independent or the LUND fragmentation. Therefore, the cluster hadronisation may give different results. The contribution R_{sea} is interesting since it contains information on the proton structure function.

Note that high-order QCD, hadronisation and resonance decays should further decrease the $\langle q^h \rangle$ since they produce an additional smearing effect which can properly be taken into account using a MC simulation.

3.3 MC Study

Fig. 6 shows the average charge of leading particles in LEPTO as a function of $\langle Q^2 \rangle$ and $\langle x \rangle$. A leading particle with a minimum value of p_Z^{Breit} was identified among all charged and neutral final-state hadrons in the current region of the Breit frame. To investigate the contribution from sea quarks, we generated a DIS sample after the rejection of struck antiquarks \bar{u} and \bar{d} from sea as well as all heavy flavour sea quarks and antiquarks. This can easily be performed using the LST(25) parameter in LEPTO, without redefinition of the structure function. Note that this method does not completely remove the contribution of sea quarks u and d to valence quarks in the proton, since LEPTO does not distinguish between light valence and sea quarks [14]. Fig. 6 also shows the average charge after the use of the cuts to reject the BGF contribution.

According to the simulation, the expected limit 0.25 is still not reached for the given energy scale. The contribution of sea quarks is very large and depends on x : At low x , sea quarks dominate and this reduces $\langle q^h \rangle$. The cuts described in Sect. 2 increase the value of the average leading-particle charge, as one expects from a decrease of R_{BGF} in (6).

4 Charm

The study of the charm production in DIS is of importance for the understanding of the sea parton densities in the nucleon. The three diagrams shown in Fig. 1 can contribute to the charm cross section. There is an evidence that the main fraction of charm quarks is created in the BGF [15], rather than through the QPM type of scattering. This, however, cannot be considered as a solid conclusion yet due to small statistics available at that time and since the LEPTO used to measure $(2 | \vec{p}_D |)/W$ in [15] had no QCDC process, which is an additional non-BGF contribution to the QPM picture at medium Q^2 .

In addition to the perturbative QCD charm mechanisms, it was suggested long time ago the hypothesis of intrinsic charm [16]. Possibilities of probing the intrinsic charm at HERA have been discussed in [17]. According to this model, the proton wave function has an additional contribution from $|uudc\bar{c}\rangle$. In this model the intrinsic charm is created due to scattering either on the intrinsic charm quark or a light valence quark, so that intrinsic $c\bar{c}$ pair moves along the proton remnants. For these cases, the only DIS processes contributing to the production of intrinsic charm are the QPM and QCDC.

One of the important issues in the intrinsic charm studies is to find a method to isolate the QPM and QCDC processes from the BGF. Having obtained a subsample with a small fraction of the BGF type of DIS events, one can perform a more detailed study of charm. Some ideas on how to suppress the BGF background in the intrinsic charm study has already been discussed in [17].

To illustrate the possibility to reduce the events with charm coming from the BGF using our method, we generated the charmed DIS events with AROMA 2.1 [18] and LEPTO 6.5 MEPS models. We used the CTEQ4M [13] structure function for both simulations. The AROMA models the charm production through the BGF, which is implemented at the LO including heavy quark mass. In the LEPTO, the BGF processes were turned off, so that all charm quarks originate from sea in the proton (charm from fragmentation can be safely neglected). The intrinsic charm was not included explicitly in this simulation: The kinematic signatures of the intrinsic charm are expected to be similar to those of the sea quark production in QPM/QCDC [17].

Applying the selection described in Sect. 2, only about 2 – 3% of the BGF events with charm passed the cuts. On the other hand, more than 20% of the events with sea charm survive the cuts, i.e. the suppression of BGF events with charm is by a factor 8-10 larger than for the QPM/QCDC type of charm production.

The reconstructed 4-momenta of charm candidates, transformed into the Breit frame, can also be used to distinguish between QPM/QCDC and BGF type of the LO events. This can be done by measuring the transverse current-region momentum of a charm hadron. Such a transverse momentum is expected to be softer for QPM/QCDC than for BGF. Another possible approach is to calculate the ratio $R = \langle N_{\text{target}} \rangle / \langle N_{\text{current}} \rangle$, where $\langle N_{\text{target}} \rangle$ ($\langle N_{\text{current}} \rangle$) is the average multiplicity of charm hadrons in the target (current) region. For QPM, $R = 0$, while for the BGF, $R > 1$. The QCDC gives also $R \neq 0$, but this value is not as large as for the BGF (see Fig 3). After applying cuts on the ratio R or the

transverse current-region momenta of charm candidates, one could obtain a sample of non-BGF charm events to be studied further.

After the BGF suppression, the resulting DIS events might contain a fraction of events with intrinsic charm, large enough to obtain an experimentally detectable excess in the charm production over the conventional QCD processes. This excess can be seen at not very high Q^2 and a sufficiently large x , i.e. in the phase-space regions where the BGF has an additional suppression.

4.1 Conclusion

In this paper we show that, in the LO formalism with multiple parton emission described by a parton shower, one can obtain a subsample of DIS events where the probability to observe QPM/QCDC type of events with (anti)quark recoiled against the proton is clearly enhanced, in contrast to DIS events without any preselection. This can be done without jet clustering algorithms that reject both QCDC and BGF type of events and suffer from ambiguity in jet definitions and misclustering at low Q^2 (jet E_T). The investigation of this subsample can provide a deeper insight into the proton structure by studying the flavour of the struck quark, indirectly, through the measurement of the leading particle charge or, more directly, by reconstructing the heavy flavour quarks. More explicitly, the first measurement is very sensitive to the sea quark contribution to the proton structure function and details in the fragmentation mechanism. The second study may allow to observe an excess in charm production over the conventional perturbative QCD mechanisms and thus to set an upper limit on the intrinsic charm inside the proton in DIS at HERA.

Note that the efficiency of the BGF rejection can be different for different cut-offs on the matrix elements. To study this, it is necessary to re-tune the LEPTO model with a new values of cut-offs in order to obtain a good description of DIS data. Moreover, rather significant reduction of the BGF processes which seen in LEPTO might be a feature of any Monte Carlo model based on matching of the first-order QCD matrix elements with softer emissions in parton showers. Presently, it is difficult to verify this point since less formal models based solely on parton showers, ARIADNE and HERWIG, do not distinguish between different types of the LO processes.

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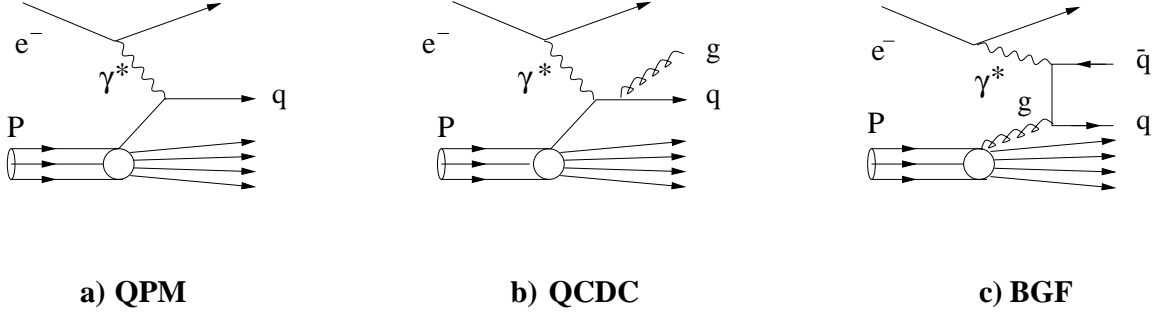


Figure 1: *QPM and the $\mathcal{O}(\alpha_s)$ QCD processes.*

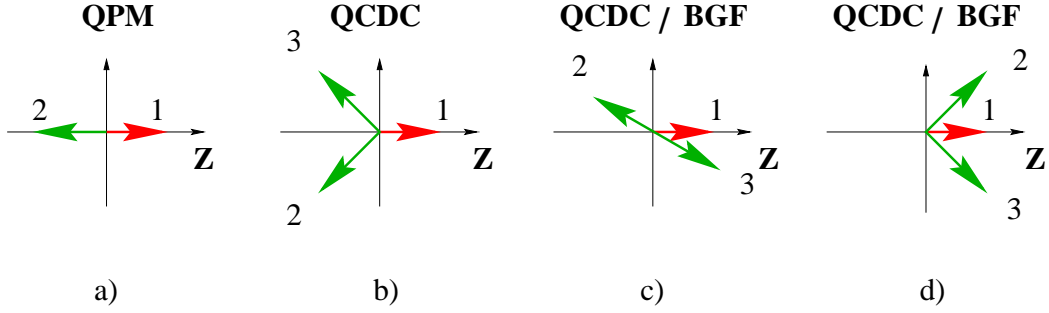


Figure 2: *Various configurations of final-state partons at the LO in the Breit frame. "1" denotes the spectator partons while "2" and "3" denote the final-state partons from the hard QCD interactions.*

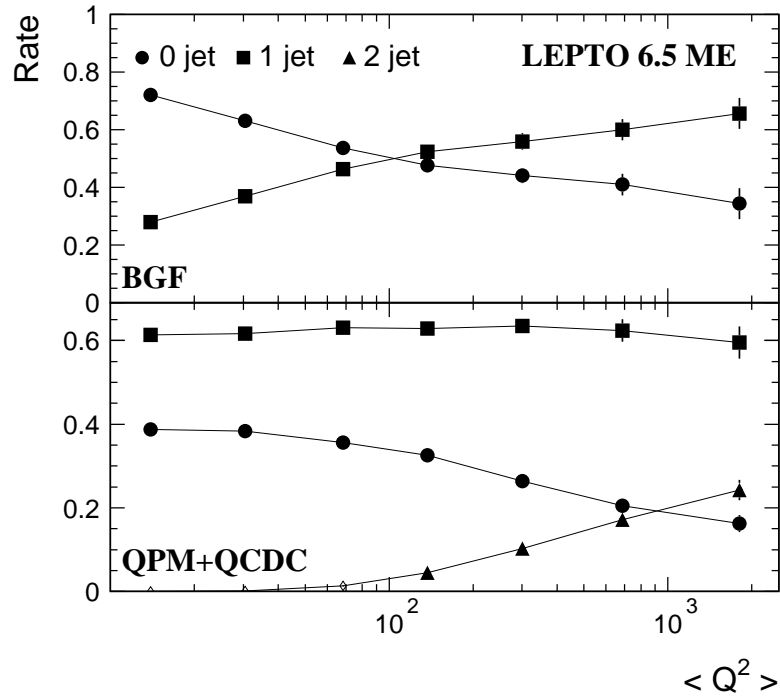


Figure 3: The production rates of various kinematic topologies of the LO partons in the current region of the Breit frame as a function of Q^2 . The rates are generated with the LEPTO model. The lines are to guide the eyes. The notation “0 jet” corresponds to empty current region, while “1 jet” and “2 jet” denote the production of one or two final-state hard partons in the current region, respectively.

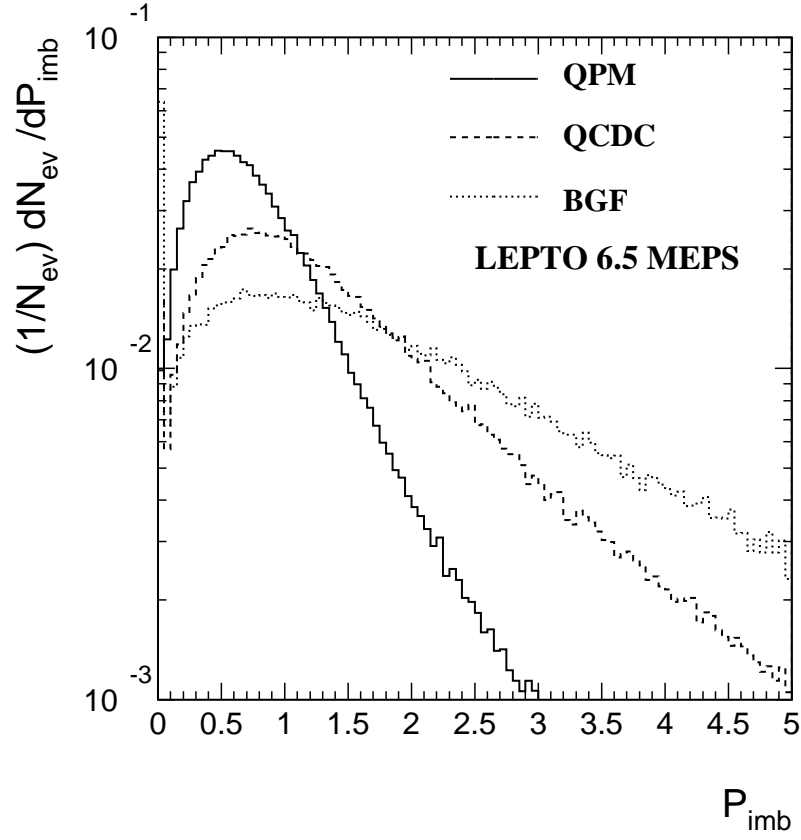


Figure 4: *The transverse imbalance of the current-region charged particles in LEPTO MEPS for the LO processes. The histograms are normalised to unity. The sharp peak at $P_{\text{imb}} = 0$ seen for BGF and QCDC corresponds to events without charged particles in the current region.*

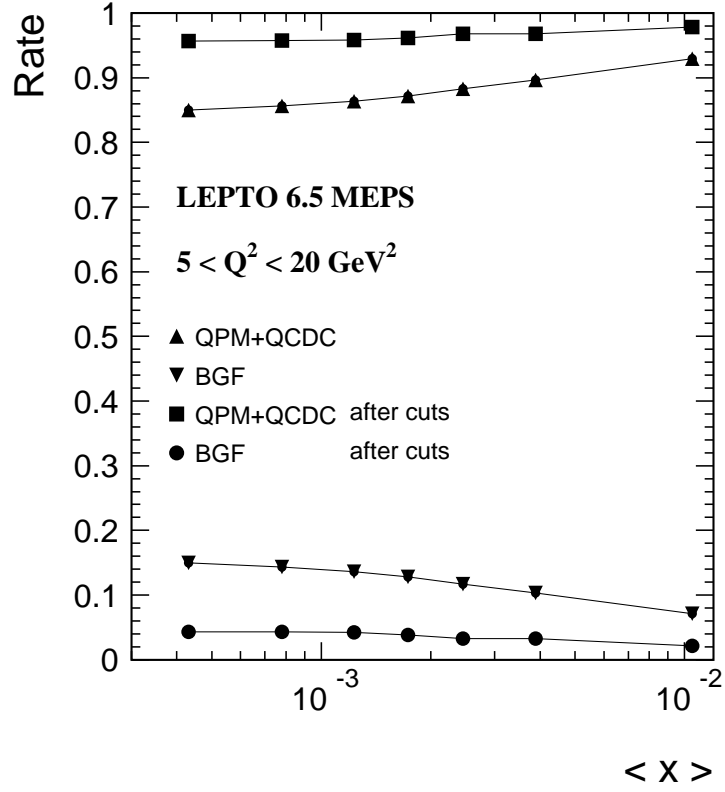


Figure 5: The production rate of the LO QCD processes in LEPTO before and after the selection procedure. The lines are to guide the eyes.

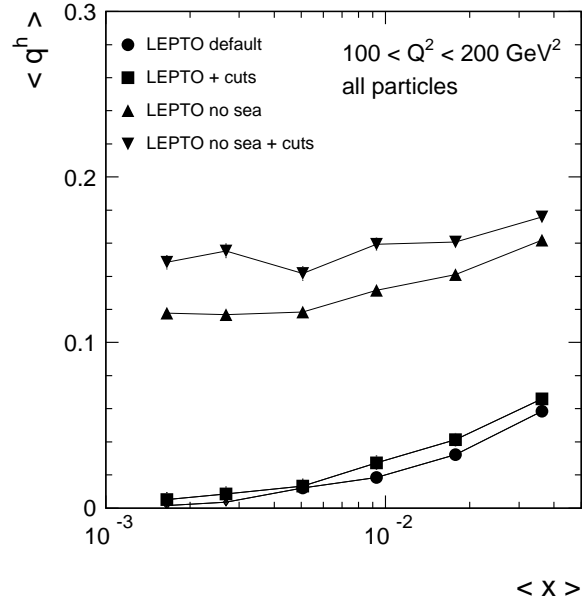
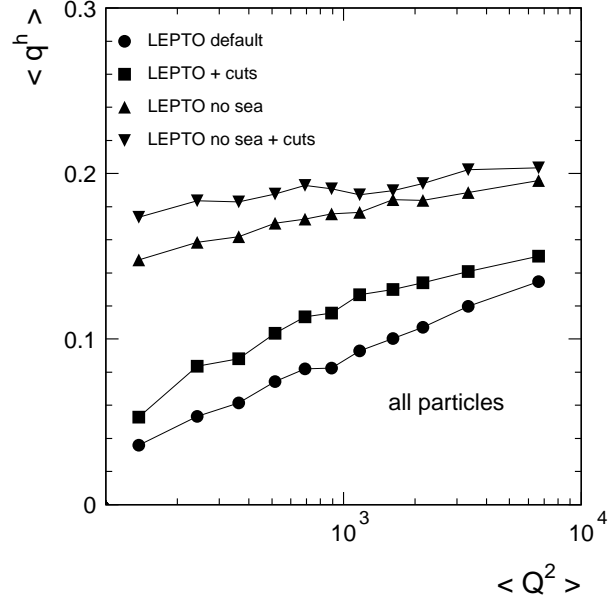


Figure 6: Average charge of leading particles before and after the BGF reduction (the label “+cuts”). The leading particles were determined using charged and neutral final-state hadrons generated with LEPTO MEPS. We also show the LEPTO predictions without sea quarks, as described in the text. The statistical uncertainties are smaller than the size of the symbols.

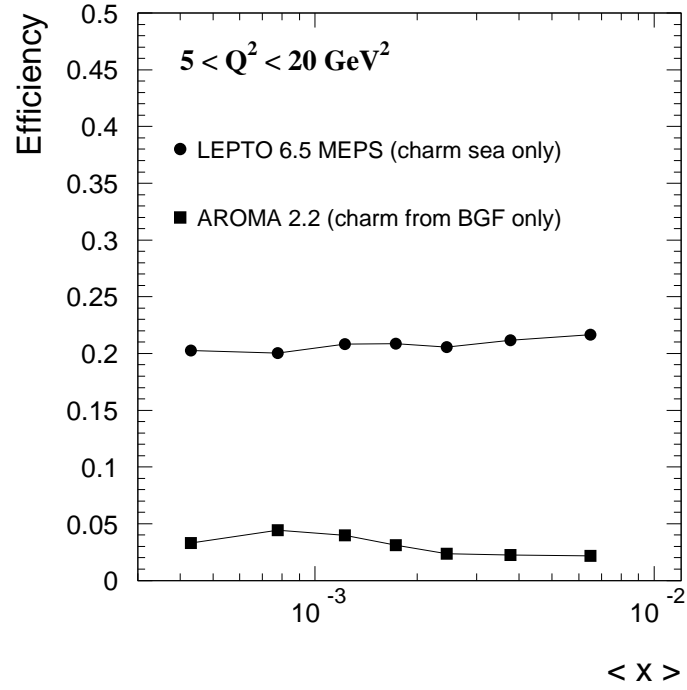


Figure 7: *The efficiency of the event selection after the BGF reduction for AROMA (charm comes from only BGF) and LEPTO (charm is created in the QPM/QCDC processes) Monte Carlo models.*